NAVAL RESEARCH

REVIEWS

JULY 1970

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Portraits in Science

Dr. Lambertsen has been closely associated for more than twenty years with the Navy's interest in improving man's performance capabilities in the sea. During this period, as a member of the faculty of the University of Pennsylvania Medical School and as an Office of Naval Research contractor, he has made outstanding research contributions not only to physiological problems related to high pressure environments, but also to aerospace environments as well as to physiology in general. Recognized for many years as an international authority in his field, he has served as a member or chairman of various advisory committees of the National Academy of Sciences/National Research Council, as consultant to the Surgeon General, U.S. Navy, as prime mover in organizing four renowned Underwater Physiology Symposia, as well as first president of the Undersea Medical Society. Currently Director of the Institute for Environmental Medicine at the University of Pennsylvania, Professor Lambertsen has recently been presented with the Ar. old B. Tuttle Award and the Albert R. Behnke, Jr. Award for his contributions to aerospace medicine and underwater medicine respectively.

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High Temperature Acoustics: Sixties' Research Spawns Seventies' Applications

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INTRODUCTION

That the Navy should be concerned with waves is obvious even to landlubbers. But while "familiar" water waves ripple 70 percent of the earth's surface, Panametrics' researchers, sponsored in part by the Acoustics Program of the Office of Naval Research, are "making waves" of their own in solid materials at temperatures up to their melting points, and in liquids, gases and plasmas.

Waves made at high temperatures are needed in order to:

- measure properties of solids—moduli, strength, *etc.*
- measure properties of fluids—viscosity, thermal conductivity, *etc.*
- characterize the state of a system—temperature, pressure, phase, flow velocity, *etc.*
- measure and/or monitor integrity of welds, especially in nuclear environments (~3 miles of welds per nuclear submarine).
- inspect and test materials nondestructively, early in the production cycle.
- measure (and thereby control) processes nondisruptively.

NATURE OF ULTRASONIC WAVES

First, we should explain that we are concerned with little, weak sound waves, small enough not to affect the materials being studied or interrogated. Second, these waves are ultrasonic, they have frequencies above 20 kHz which is above the range of human hearing. Such waves can be guided inside wires which are thin compared to wavelength, or beamed, much like a searchlight, inside large, bulky bodies, provided the beam diameter is large compared to wavelength. Third, as these waves cruise through their tour of duty within a material, they have a chance to rub elbows with all the atoms, grains, boundaries, impurities, crystal defects, and stresses in their path. From such experiences, the waves become informed of conditions in the material.

Because conditions in solids can be so complicated, one poor little wave could easily become overwhelmed and confused. To make things

easier, we use the proven strategy, divide and conquer. That is, we use several different wave types, several different frequencies, different paths, even several different structural forms of the same material elements such as single crystal *vs* polycrystal to divide the materials variables among the different forms of acoustical interrogation at our disposal.

Certain characteristics of fluids such as temperature, flow rate, pressure, and viscosity, can also be determined from ultrasonic measurements.

Orbits. Different types of waves vibrate particles in their path in different orbits or patterns. For example, longitudinal or extensional waves move particles back and forth in the direction of the sound ray. Transverse shear waves cause particle motion perpendicular to the ray. Lamb waves are combinations of longitudinal and shear that travel in sheets. Rayleigh waves similarly combine longitudinal and shear actions into elliptical particle orbits near the surface of materials. Love waves are a transverse vibration found in low-velocity coatings, "slow coats," atop a stiffer substrate. Many will recognize that these ultrasonic waves have low frequency counterparts of importance in seismic and other studies of the earth, including solid strata, water, ice, air, and boundary layers.

Wavelengths and Frequencies. For purposes of acoustical analysis it is convenient to divide testing applications into three categories according to whether at least one cross-sectional dimension of the body under test is (1) small compared to wavelength, (2) comparable to wavelength, or (3) large compared to wavelength.

In the first category we find fibers, thin wires, thin-walled tubes, and ribbon, generally tested below about 1 MHz. Extensional and torsional waves are appropriate to this category. At 1 MHz, the extensional wavelength is ~0.2 inch, or ~5 mm.

The second category includes sheet and tubing, typically tested with Lamb waves, and coatings of lower shear wave velocity than the substrate, tested with Love waves. Test frequencies are on the order of 1 to 10 MHz.

The third category includes bulky materials such as steel ingots or billets, and large castings. Longitudinal, transverse shear and Rayleigh (surface) waves commonly interrogate such materials in the 1 to 10 MHz range. Rayleigh waves interrogate the surface to a depth of about one wavelength, at 10 MHz, ~0.010 inch, or 0.25 mm. The beauty of Rayleigh waves is that they are only skin deep.

Occasionally test frequencies as high as 25 MHz are used, while in special applications, some researchers operate in the praetersonic range—above 500 MHz. On the opposite extreme, highly attenuating materials, including plastics, elastomers, some composites, concrete,

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viscous liquids, and large grained materials may require frequencies below 1 MHz, depending on the path length.

Frequencies above ~1 MHz are usually generated and detected using piezoelectric transducer materials. Below ~1 MHz, magnetostrictive transducers are more common. There is, however, substantial overlap. Also, new transducer materials, and even new transduction principles, continually enter the scene.

Perhaps it is now plausible that by directing "sonic speedsters" through materials, one can acoustically interrogate materials fast—at the speed of sound. By properly posing and sequencing the questions, and analyzing the responses, a truer picture of the surface and interior of materials gradually comes into focus.

We are beginning to ask materials such questions as:

- How stiff are you? (Young's modulus, shear modulus, Poisson's ratio.)
- Are you annealed yet?
- Are you fed up—saturated—with carbon?
- Are your insides as hot as your outsides?
- Are you ready to be hot worked?
- Do you contain molten portions? If so, how thick is your skin?
- Do you feel tired—fatigued—unable to withstand on-the-job stresses much longer?
- Are you qualified for service—or are you headed for the scrap bin?

To pose these and other questions, special probes are needed. These probes contain electroacoustic transducers. You may wish to think of them as devices which translate our questions into appropriate waves.

ULTRASONIC MEASURING SYSTEMS FOR USE AT HIGH TEMPERATURE

Under ONR support, high temperature ultrasonic measuring systems have been developed for materials having dimensions both thin and thick compared to wavelength. While obvious to many, it perhaps should be mentioned that some materials are most easily prepared in slender cross sections such as fibers and whiskers. Others, however, are made in large dimensions, and removal of a small section is difficult without modifying the elastic properties of the resulting specimen.

Bulk Material Measurements. A typical pulse-echo arrangement for testing bodies thick compared to wavelength is shown in Figure 1. The buffer rod touches the hot specimen only momentarily, minimizing heat transfer. Echoes originate at the front and back of the specimen, or at other internal discontinuities.

Thin Material Measurements. Pulse-echo testing of specimens thin compared to wavelength is illustrated in Figure 2. Here, heat transfer

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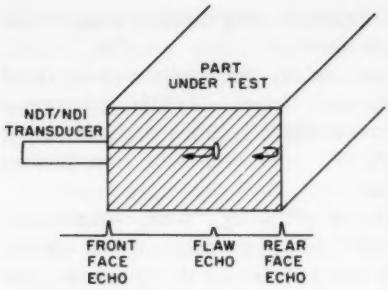
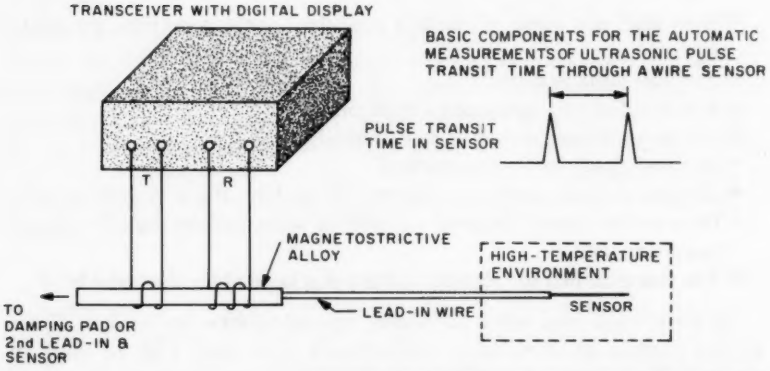


Figure 1 – Ultrasonic testing of body of cross sectional dimensions large compared to wavelength. Echoes give flaw information, plus thickness, if temperature or velocity is known; or temperature, if thickness is known (see also Figures 3, 6, 7, and 11).



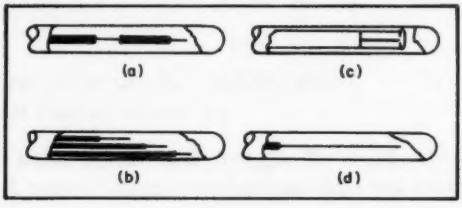


Figure 2 – Ultrasonic measurements in bodies thin compared to wavelength. At right, sensor designs for temperature profiling using serial and parallel sensors. Up to ten sensors can be used in series, with only a single lead-out wire.

is less of a problem, and continuous contact of the buffer or lead-in line to the specimen (sensor) is tolerable. As before, echoes originate at the front and rear of the specimen.

In both cases, transit times and amplitudes are observed, from which velocity and attenuation are calculated. These propagation characteristics, in turn, may be related to physical properties of interest in the specimen.

Assuming for the moment that the probes containing electro-acoustic transducers necessary for generating and detecting the ultrasonic waves are available, a practical question arises immediately: How do

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you couple sound waves into the item you wish to test? This problem becomes more complicated if the item is in motion, or remote (say, under liquid sodium in a breeder reactor), or at high temperature (continuous cast steel). We will consider only two limiting cases: dimensions small or large compared to wavelength. Before getting into the thin and the thick of it, we first consider coupling problems common to both extremes.

Coupling Waves Into Wires. Suppose you want to get sound into a wire. What's the easiest way? The answer depends partly on the material. If the wire is magnetostrictive—say, nickel, below its Curie point—simply encircle it with a coil. The coil's flux links with the wire. Pulses or continuous waves can be readily injected into and extracted out of the wire, to measure or indicate various qualities of the wire. For example, longitudinal or transverse flaws can be detected.

If the wire is *not* magnetostrictive, we presently see three main coupling choices: (1) couple acoustically/mechanically (by bonding, by using an intermediate fluid, or by pressure); (2) couple optically (laser techniques); (3) couple electromagnetically ("eddy-sonics" or electromagnetic interactions in a conductor.).

Coupling with a fluid film, to transfer an acoustic wave from a transducer to a solid, is in common use today. The laser and electromagnetic methods were developed by other investigators only this past decade, and are not yet widely used.

In the laser technique the energy of a laser beam impacting on a solid gives rise to ultrasonic waves—sort of an optical-acoustical interaction.

In the electromagnetic or "eddy-sonic" methods, electrical energy is converted directly into mechanical energy at the surface of the metal, without the use of a couplant. The inverse process also occurs. Physical contact with the metal surface is not required since small wire coils adjacent to the surfaces can be used to produce and detect the ultrasonic wave. Both artificial flaws and naturally occurring inhomogeneities in aluminum bars and rods have been detected. The material under test can be fixed in position or can be in motion since the coupling is through an air gap.

Coupling Waves Into Bulk Solids. Traditionally, longitudinal waves have been coupled through a liquid such as water or oil. Shear waves have been coupled by bonding the transducer to the part. At oblique incidence, longitudinal and shear can be coupled *via* a thin liquid layer. Fortunately, one technique, pressure coupling, works for both waves, from room temperature up to thousands of degrees. Typical coupling pressures are in the 1000 to 10,000 psi range.

The potential scope of ultrasonic shear wave testing has generally not yet been exploited because of the inherent limitations of presently used bonding, mode conversion or other highly specialized coupling

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methods. Such shortcomings are substantially avoided by means of pressure or optical contact coupling of SV and SH shear waves at all angles of incidence, or by means of a fluid film for coupling SV shear waves at oblique incidence.

To avoid excessive heating of the transducer, only momentary contact, about one-tenth of a second, up to several seconds, is used.* This brief contact is more than enough to interrogate the material, as sound can course through most paths of interest in a few microseconds. The brief contact also ensures that the hot part is not cooled too much.

Under the ONR program, this method was developed to measure Young's modulus, shear modulus, and Poisson's ratio in solids beyond 3500°F. With industry support, the method is now being developed for nondestructive testing (NDT) applications such as measuring skin thickness of continuous cast steel, hot steel tubing eccentricity, and flaws at high temperature.

Also of possible future significance, the laser and eddy-sonic methods of coupling are applicable at high temperature. Thus, in the seventies the variety of high temperature coupling methods, together with an increasing availability of high Curie point transducer materials, should offer interesting testing possibilities for ultrasonics at high temperature.

The significance of high temperature testing is that materials which are normally made or joined at high temperature can be characterized early in their production cycle. Thus undesirable characteristics can be corrected in time to avoid costly processing of material which, unbeknownst to the producer, would be destined for the scrap heap.

APPLICATIONS

Measurements of Basic Properties

Elastic Moduli. By measuring the time t for a sound pulse to traverse a known distance L, the Young's and shear moduli are calculated from the simple expressions $E = \rho\,(L/t_0)^2$ and $G = \rho\,(L/t_T)^2$ where ρ = density, t_0 = extensional wave transit time and t_T = shear or torsional wave transit time. These transit times usually increase with temperature (Figure 3). Panametrics' Panatherm® 5010 is used to measure these times automatically. This instrument can feed t_0 and t_T, in binary coded decimal form, into standard calculating equipment (Figure 4) so that moduli can be determined automatically, and displayed or printed out as a function of temperature. Data have been obtained to the melting points of molybdenum, rhenium, and tungsten.

*Momentary contact apparatus, as well as many of the ultrasonic probes and measuring systems described here, are covered by numerous U.S. and foreign patents pending or issued.

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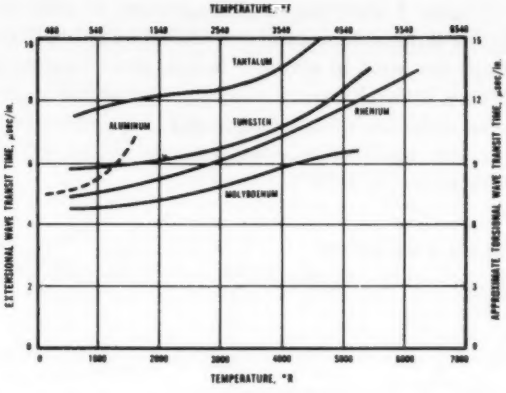

Figure 3 – Transit time *vs* temperature for several thin-wire temperature sensors

Poisson's Ratio. Poisson's ratio σ is readily obtained from E and G: $\sigma = E/2G - 1 = t\mathrm{T}^2/2t_0^2 - 1$. E, G and σ can all be obtained essentially simultaneously on a single specimen over the entire temperature range of interest, from cryogenic up to melting temperatures.

Annealing. Using a self-heating technique, we are able to find out how long a specimen must be kept at a particular temperature before its elastic properties have essentially reached their asymptotic (equilibrium) values at that temperature. Such measurements could provide an easier way to optimize heat treating operations.

Figure 4 – Elastic moduli and Poisson's ratio are determined automatically in closed-loop system. Panatherm 5010 measures transit times, which are fed, in 16 line BCD form, to programmed Wang calculating equipment. Readout (or print-out) is in millions of psi for Young's and shear moduli.

Diffusion. Figure 5 illustrates a measurement of diffusion of carbon into rhenium at a temperature of about 4000°F. Carbon has diffused all the way through the wire in about 3 hours, since heating beyond that time leads to very little change in velocity. (Subsequent chemical analysis verified the diffusion of 0.4 weight percent carbon in the rhenium wire, which is the equilibrium concentration shown by the rhenium/carbon phase diagram for 4000°F.)

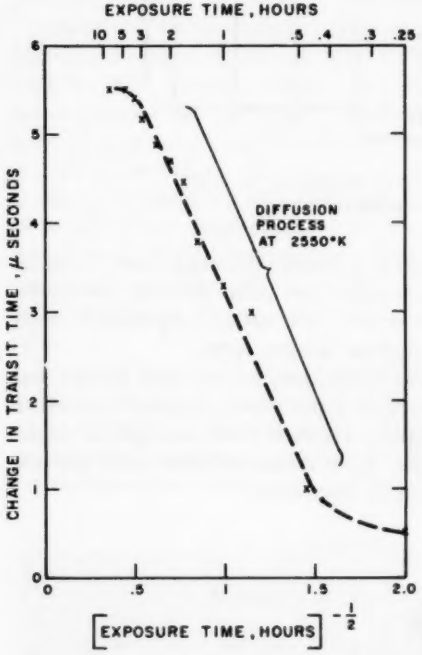
EXPOSURE TIME, HOURS
10 5 3 2 1 .5 .4 .3 .25
CHANGE IN TRANSIT TIME, μ SECONDS
DIFFUSION PROCESS AT 2550°K
0 .5 1 1.5 2.0
[EXPOSURE TIME, HOURS] $^{-\frac{1}{2}}$

Figure 5 — Diffusion of carbon into rhenium at ~2550°K indicated by linear portion of plot. Data obtained using self-heated rhenium wire, 1/2 mm dia × 50 mm long, surrounded by graphite felt. Self-heating current ~20 amperes.

Measurements for Process Control

Temperature. Sound velocity is a function of temperature, in solids, liquids and gases (Figure 6). Ultrasound may be sent through the medium itself whose temperature is to be determined, or through a foreign sensor such as a thin wire.

When the medium itself is its own sensor, there is usually little question of thermal equilibrium. The measurement can be achieved with essentially no perturbation of the temperature field—sometimes with even no penetration of the container.

For gases, this is especially attractive in applications such as turbine inlet gas thermometry in jet engines. We have demonstrated the "medium itself" technique at NASA test sites on small rocket engines, and

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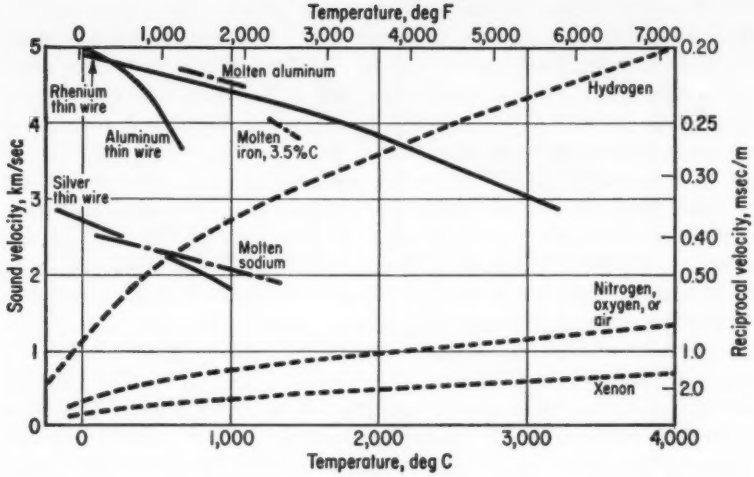

Figure 6 — Sound generally travels slower as temperature goes up in solids and liquids, and speeds up in gases at higher temperatures. The velocities plotted for solids are for extensional waves; these waves propagate in wires that are thin compared to wavelength.

across two-foot paths of flowing nitrogen; at General Electric-Evendale, on combustor rigs simulating jet engine turbine inlet conditions; and at Panametrics, in plasma jets, shock tubes, muffle tube furnaces, and in air at 10^{-4} atm (rarefied air testing was part of an ONR-supported feasibility study of upper atmospheric sonic thermometry). Generally, our main interest has been in the 70 to 40,000°F range. At the National Bureau of Standards, investigators have independently developed an ultrasonic interferometer method, using helium gas itself as the sensor for a primary temperature standard in the 2 to 20°K range.

For liquids, the medium itself technique is attractive because of accuracy, longevity, and lack of penetration. We demonstrated the technique in an AEC program by transmitting sound through liquid sodium contained in a 10-inch diameter stainless steel pipe, without drilling through or otherwise modifying the pipe.

For solids, the technique is attractive because it gives information about the temperature inside the part. As an example, if you are heating a steel ingot or forging prior to hot working, and wish to know when it's all up to temperature, sound waves can give you the answer. In one method, you simply observe the transit time over a central path. When this time stops increasing, that path is at an equilibrium temperature. Further exposure in a given furnace is wasteful. In a second method, transit times are compared over different paths such as near the surface or across the middle. This also tells when the middle is as hot as the

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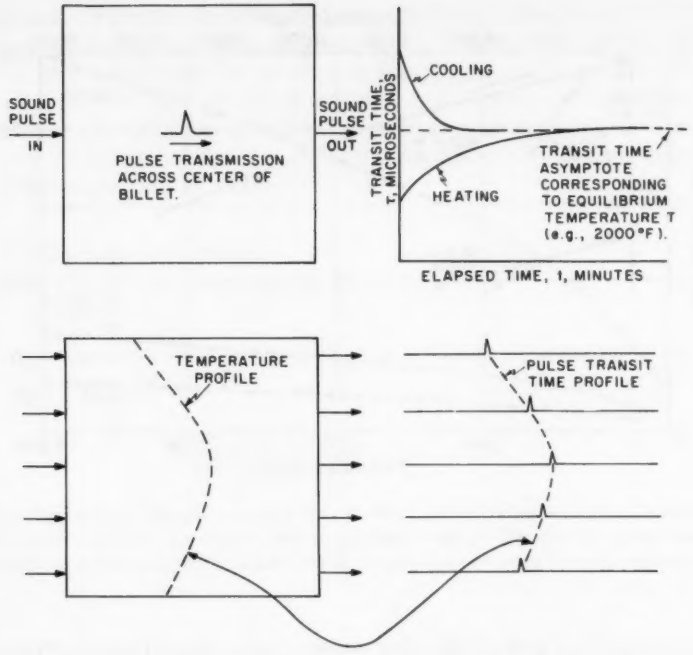

Figure 7 — Ultrasonic determination of temperature distribution inside large metal billets. (Top): Using only one central path, slope of τ *vs* t curve shows approach to equilibrium. When $d\tau/dt = 0$, billet has reached a steady temperature. Value of τ gives average T across path inside billet. (Bottom): Using several parallel paths, transit time profile can be interpreted in terms of temperature profile inside billet.

surface (Figure 7). If the path lengths and composition are known, these methods give the actual temperature history. Otherwise they give relative temperatures, complementary to optical or thermocouple temperature readings of the surface.

The medium itself technique is especially attractive in offering the possibility of nondisruptive measurements for process control; however, uncertainties in the medium or path may often suggest that alternative, foreign sensors be used.

Measuring time between echoes in a thin-wire sensor may provide a useful measure of temperature, especially at high temperatures (to 5400°F) and in nuclear environments. In most solids, as temperature increases sound velocity decreases. So pulse transit time increases directly as temperature increases.

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Panametrics Panatherm 5010 system automatically measures the time for pulses to traverse a wire sensor (Figure 2). An electrical driving pulse energizes the transducer (usually magnetostrictive), launching ultrasonic stress pulses. The ultrasonic pulse continues down the lead-in line. At the sensor, this pulse is reflected, partly from the beginning and partly from the end of the sensor. These two echoes return along the lead-in wire. On passing through the receiver coil, which may be the same coil as for the transmitter, the ultrasonic stress pulses generate voltage pulses. The time interval between these voltage pulses is measured automatically to 0.1 μsec. This accuracy, together with sensor material, length, number of echo reverberations selected, temperature range, and vibration mode, determines the temperature sensitivity.

Typically, a 2-in. refractory metal sensor, using the first echo pair for extensional waves, yields temperature sensitivity better than 1 percent at 5000°F. Sensitivities of 0.1 percent can be achieved with a longer sensor, multiple echoes, or torsional waves. By connecting sensors in series, temperatures can be determined in as many as 10 adjacent locations, to give profile information, using only one line.

Thin-wire systems offer two principal advantages over thermocouples: a wider choice of sensor materials and of geometries. For example, at low temperatures, say up to 1000°F, aluminum serves well as an ultrasonic sensor. To 2000°F, stainless steel is a candidate. Sapphire holds up in oxidizing environments to at least 3000°F. Ruthenium and molybdenum withstand 4000°F, while rhenium and tungsten/rhenium alloys appear useful up to 6000°F.

As new refractory materials become available, they become candidate sensors. The ultrasonic measurement depends on density and elastic properties of the sensor, not electrical properties. This characteristic avoids the need for a high temperature electrical insulator, overcoming another difficulty inherent in thermocouples. In certain nuclear applications, parts of the fuel pin itself may serve as sensors.

Choice of sensor geometries includes very thin wire, ribbons, and tubes with monolithic, one-piece, weld-free construction of a single material. In some cases the sensor may be shaped to average temperature over a prescribed path. Typical dimensions for the temperature sensor range from below .001 in. to 1/8 in. diameter, and lengths from 1/2 in. to 10 ft.

The following limitations apply to thin-wire systems:

- Temperature is averaged over length of sensor, not at a point.
- Attenuation may obscure echoes from sensor if too much of lead-in is at an excessive temperature.
- Sensor must generally be isolated acoustically, and sometimes metallurgically, from neighboring solid mediums.
- Sensitivity degrades at low temperature.
- Applications experience is still meager.

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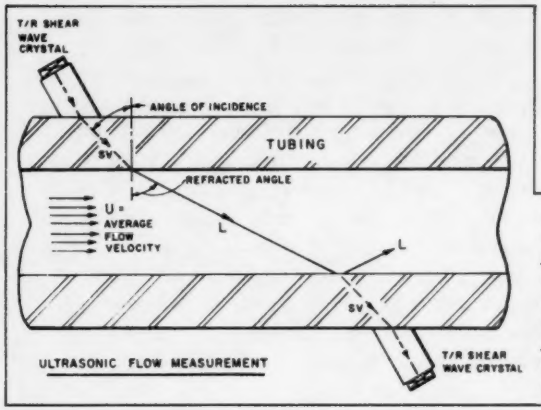
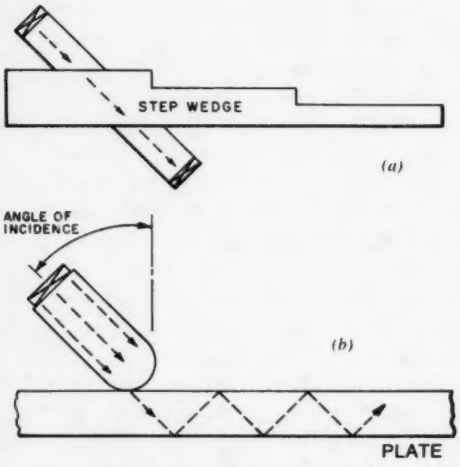
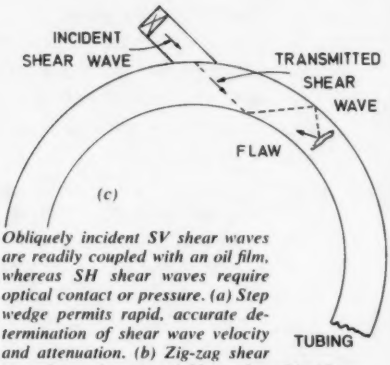


Measurement of transit time upstream and downstream yields average fluid flow velocity. Similarly, measurements along chords could indicate flow profiles. Incident shear wave launches a longitudinal wave which is refracted at a more favorable angle for flow measurements than if the incident wave were longitudinal.





Obliquely incident SV shear waves are readily coupled with an oil film, whereas SH shear waves require optical contact or pressure. (a) Step wedge permits rapid, accurate determination of shear wave velocity and attenuation. (b) Zig-zag shear wave inspection at variable angles of incidence. (c) Curved body such as tubing wall can be tested with zig-zagging SV waves over a broad but limited range of angles of incidence, and with zig-zagging SH waves at virtually all angles of incidence.

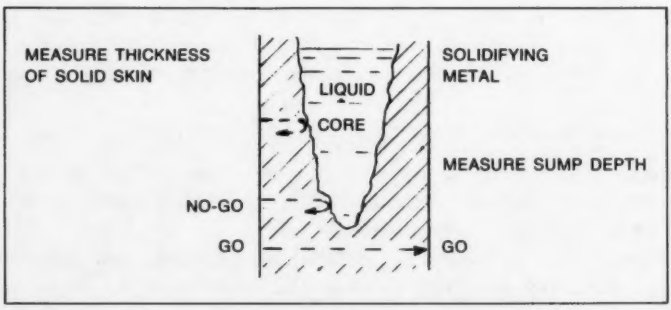
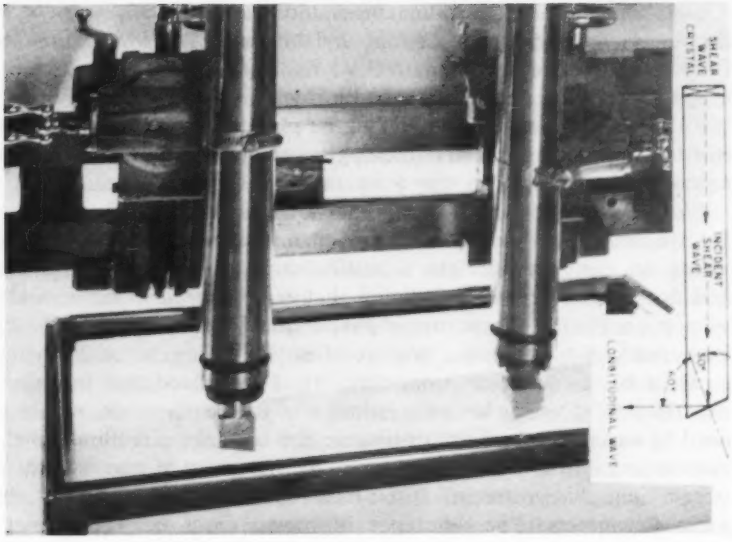
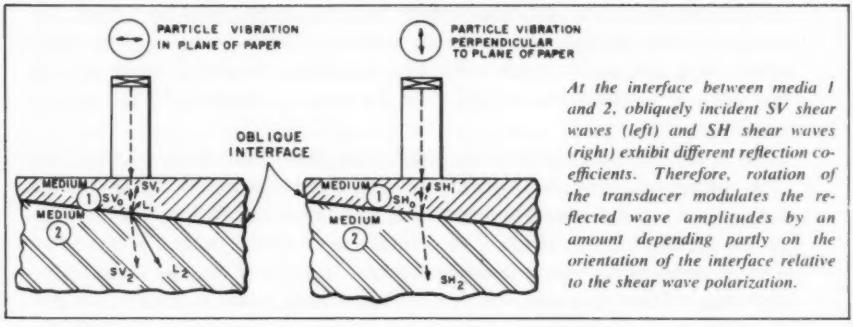


Figure 8 – Ultrasonic probes using shear wave crystals





At the interface between media 1 and 2, obliquely incident SV shear waves (left) and SH shear waves (right) exhibit different reflection coefficients. Therefore, rotation of the transducer modulates the reflected wave amplitudes by an amount depending partly on the orientation of the interface relative to the shear wave polarization.

Obliquely incident shear wave in acrylic is slow enough to launch Rayleigh wave in low velocity materials such as graphite. To test metals or ceramics of higher Rayleigh wave velocity, other low-loss probe materials may be selected and operated in the SV shear mode at high frequency, 10 MHz and above.

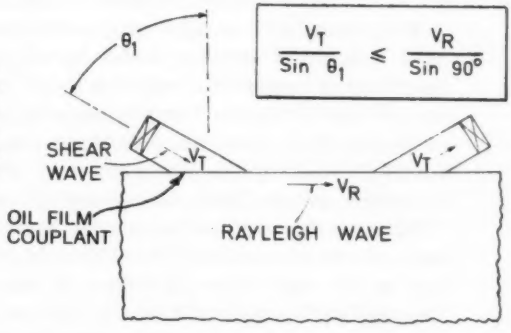


Figure 8 (Continued) – Ultrasonic probes using shear wave crystals

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Concluding this section on temperature measurement, we note that the American Society for Testing and Materials (ASTM), Committee E-20 established a subcommittee VI on Acoustical Thermometers at a special meeting held in their Philadelphia headquarters in April, 1969. Thus, we see acoustics taking its place alongside thermoelectric, resistance, pyrometric, and liquid-in-glass thermometers as a recognized, practical means for measuring temperature.

Flow. Sir Isaac Newton, well known for his analysis of gravitational fields upon apples and other bodies, should also be credited with providing an early insight into acoustical measurements of temperature and flow. He correctly calculated that sound speed in air should be proportional to the square root of temperature; unfortunately he used the isothermal, not adiabatic, compressibility, leading to a 20 percent error in his constant of proportionality. He realized that in order to experimentally verify his calculations out in the open air, one would need to measure sound transit time in two opposite directions, to eliminate errors due to wind. Conversely, measurement of transit time "upstream" and "downstream" is the basis of sonic anemometers or ultrasonic flowmeters. The difference in transit times is proportional to flow. The average transit time gives the temperature.

More recently, the Doppler effect has also been used as a basis for ultrasonic flow-metry. Here, the frequency shift of a sound wave scattered off particles or other reflecting interfaces in the flowing stream provides a useful measure of flow velocity compared to the sound velocity.

To date, our contributions to measuring flow stem from recognizing that ultrasonic flow measurements could be improved by using an obliquely incident shear wave, instead of the usual longitudinal wave, as the incident beam (Figure 8). We are also trying to determine what type of beam pattern best samples the flow. Fluids, of course, do not support shear. Therefore one is ordinarily not strongly motivated to consider shear waves to launch the desired longitudinal wave in the fluid. While not immediately obvious, however, it turns out that at oblique incidence, a shear wave with components in the plane of incidence (SV) can be mode converted to yield, under the right conditions, a more efficient launching of longitudinal waves in fluids, than if longitudinal waves were used in the first place. Further, since shear waves are about half as fast as longitudinal waves, they yield a wave more favorably refracted towards the axis of the fluid column. This gives a factor of 2 to 3 improvement in sensitivity, for a given geometry and frequency.

We have demonstrated ultrasonic flow measuring capabilities in pipes from 1/2 to 10 inches (13 to 250 mm) diameter, without any penetration of the pipe. The extensions of this capability to jet engine fuel lines and nuclear reactor coolants are now being investigated.

If we turn inside out the problem of measuring water flow through

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a metal pipe, we have the problem of measuring the flow of a "pipe," such as a naval vessel, through water. Will both these problems be solved with ultrasound? "Time (or phase) will tell."

Regarding flow in the biomedical area, we are cooperating with the National Institute of Health. We provided special transducers for use with an accurate, sensitive blood flowmeter that ultimately will not penetrate the container. We also demonstrated the feasibility of ultrasonic measurement of cardiac output in terms of ventricular displacement of an artificial heart, using a transducer mounted in the septum.

The concept of measuring temperature and flow with the same pair of transducers, and a common readout instrument, is not new. Dual purpose sensors are becoming increasingly popular. For example, by sticking a small thermocouple inside a bent tube, a Pitot tube becomes a "pee-tee" tube with pressure and temperature capabilities. Dual purpose sensors and readout electronics are now available for moisture and temperature, strain and temperature. Ultrasonics, however, offers probably unique advantages with respect to two or more measurements over a single lead-out wire from the sensed region to the readout equipment. Alternatively, one temperature plus several other environmental parameters could be measured.

Besides temperature and flow, what about ultrasonic measurements of other process variables—pressure, viscosity, composition, turbulence, arrival of or location of interfaces, liquid level, thickness, state, boiling, quality, *etc.*? While the need to measure any one of the above parameters may not always justify introducing into a plant a "new" technique that has not been fully demonstrated, the distinct likelihood of ultimately being able to measure a number of important process parameters with one technique—ultrasonics—suggests that even conservative organizations will ultimately need to evaluate this "unheard of" approach.

Pressure. In an ideal gas, pressure affects sound propagation in two ways. First, the absorption coefficient α is inversely proportional to pressure. This means that at high pressure, sound is less quickly attenuated. Of practical importance, as pressure (and density) increases, the transmission coefficient increases. This is because the gas acoustic impedance begins to approach that of the transducer or buffer rod. The net result is that the received signal amplitude increases markedly as gas pressure increases. For example, in tests we conducted for NASA at their Plumbrook heat transfer facility, measurements in hot, flowing nitrogen across a 2 ft (600 mm) diameter path were quite difficult until pressure was increased to ~100 psi. From ~100 psi to ~1000 psi, signals were readable. This result, theoretically predicted and experimentally verified, is also important with respect to the future jet engines which will operate at high compression ratios. In some cases, the turbine inlet gas pressure always will be over 100 psi. Therefore, it will be easier to get sound across the gas itself, when measuring temperature, much

easier than it would have been in the past. At high altitudes, where inlet pressures will be small, even for high compression ratios, the proper selection of frequency, to overcome attenuation, becomes especially important.

The second effect of high pressure on sound propagation in a gas is a consequence of the gas no longer being ideal. As you might expect, as the molecules get squeezed closer together, the sound speed increases (Figure 9).

To exploit both of the above effects of pressure on sound propagation in a gas, we have measured the pressure inside a common man-size 6000 psi bottle of gas at room temperature. Access was from the outside

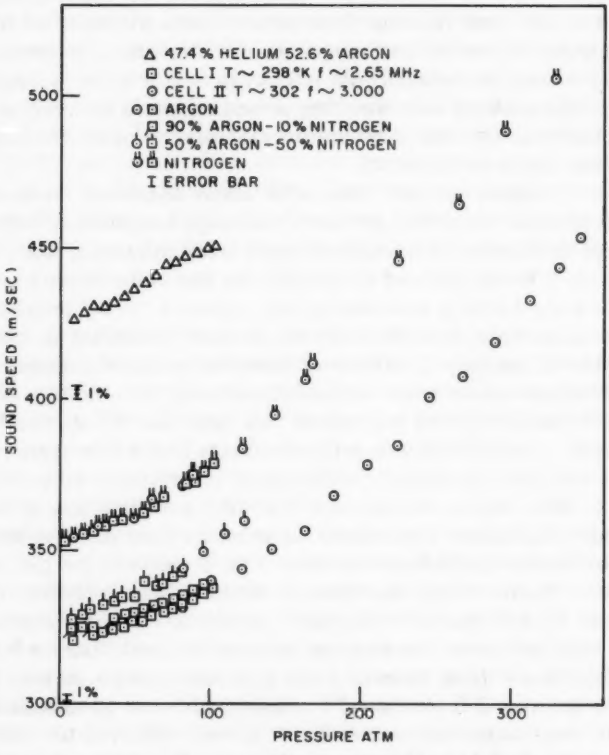

Figure 9 – Sound speed *vs* pressure in the nitrogen-argon system and a 47.4 percent helium-52.6 percent argon mixture. Data such as these provide one basis for measuring gas pressure inside containers, with virtually no penetration of the container wall. Only the sound beam "penetrates" the wall.

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only, without any penetration of the steel bottle. This was done by grease-coupling a transducer to the outside of the bottle, and reading the echo from the opposite wall. This same technique could be applied to scanning, monitoring, leak-testing or inspecting pressure vessels, especially vessels into which one does not like to install an ordinary pressure gage for reasons of leak-tightness, inaccessibility.

In liquids and solids, where the molecules are already close together, increasing pressure usually has only a very small effect on sound propagation. However, in some instances, there may be possibilities of getting an indirect liquid pressure reading by measuring pressure in a small volume of gas so contained as to be at the same pressure as the adjacent liquid.

In solids the pressure or stress affects the velocities of different wave modes depending on the material, texture, vibration type, and vibration direction (polarization) relative to the stress axis. This provides a basis for measuring surface and internal stress, or stress-induced anisotropy.

In passing, we perhaps should note that if pressures are high enough to cause crack growth at stress risers, noises are produced, "acoustic emission" (Figure 10). These can be heard by ultrasonic transducers fastened to the region in question, or by remote transducers connected *via* a thin wire transmission line several inches up to 30 ft (~10 m) long. An obvious potential application is monitoring welds in nuclear submarines during the long intervals between overhaul inspection. This could contribute substantially to submarine safety and reliability. Acoustic emission measurements can be made at elevated temperature too. For example, one might monitor jet engine turbine blades, listening for sounds of incipient failure due to subsurface defects. The point is: "Learn to Listen—Use Acoustic Emission."

Viscosity. In an ideal gas, the absorption coefficient α is directly proportional to viscosity η. Accordingly, η has been determined in argon from room temperature up to ~20,000°F from observations of sound attenuation. Interestingly, the gas temperature was measured with the very same pulse used to get α.

In polymeric liquids the relation between α and η is much more complicated. Nevertheless, experimentally we have found that for two liquids simulating the viscosity of a particular fluid at the beginning and end of a polymerization process, α was substantially higher for the "polymers" compared to "monomers." This test was done similar to the pressure cylinder (gas bottle) case, from the outside only. It would appear that thixotropic fluids could be measured in a pipe of varying cross section. Here one would look for the effect of flow velocity on α. corresponding to the effect of flow on viscosity η.

As possible parallels to viscosity, we may consider grain boundary friction, dislocation damping, interstitial motion, *etc.* Motions of particles

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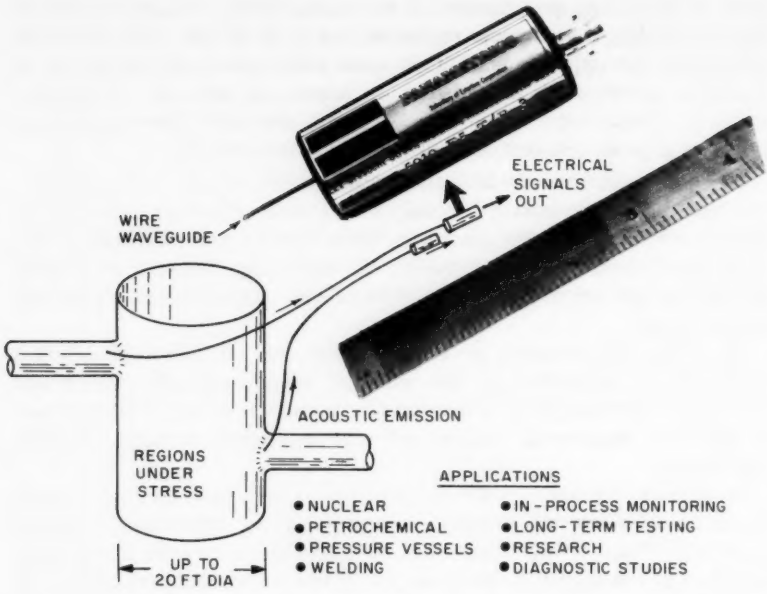

Physical Principles: (1) As a crack propagates, it emits sound pulses, acoustic emission. By listening for these emissions, one can detect incipient failure, and take corrective action.

(2) For remote sensing, or for measurements of parts at temperatures up to 5000°F, well above the useful range of ordinary transducers, a thin wire waveguide is used to convey the acoustic emissions from the point in question to a convenient monitoring station. Distances may range from a few inches to at least 30 feet (~10 m).

Installation: Customer joins wire to part in question by epoxy, braze or weld. Pressure coupling may sometimes be used. Transducer normally includes a standard 3 ft (~1 m) wire waveguide. If necessary, customer or Panametrics can connect extension lead wire (typically 1/16 inch (~1.5 mm) dia stainless steel) from end of standard waveguide to part being tested.

Figure 10 – Remote and/or high temperature acoustic emission transducers

or aggregates of particles can be thermally activated and can couple to pressure gradients supplied by ultrasonic waves. For several refractory metals studied in the ONR program, it has been observed that sound attenuation increases markedly at a temperature in the vicinity of the recrystallization temperature for each metal in question. Some 30 years ago, Förster and Köster found a similar sudden rise in aluminum and magnesium and attributed this to the glide planes becoming active and

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also noted that these were the temperatures at which the material became relatively malleable. Thus, measurements of attenuation might be used to tell when a material was ready to be hot worked.

Nondestructive Testing (NDT). Ultrasonic methods for NDT have been developed since the thirties. Measurements of flaws, defects, voids, cracks, inclusions, thickness, and numerous other departures from specifications are widely used throughout the industrial world. Many of the techniques are useful in biomedical applications.

Until recently, Panametrics' contributions to NDT were mostly limited to high temperature applications of the momentary contact technique developed under ONR support. While there are several acoustic or ultrasonic ways of interrogating hot solids in the laboratory, so far the momentary contact technique appears, at least to some observers, as the ultrasonic method most likely to graduate from the laboratory into the field for routine inspection of production material. In tests at different steel mills, for example, the technique has yielded information on billet temperature (rear face echo in 4 in. (100 mm) section), coarse grain/fine grain interface echo from chill zone end (which occurs in some casting circumstances), and liquid/solid interface (monitored during ingot solidification). We have also studied the "pipe" defect—an axial void—up to 2000°F. Applications to welding, remote acoustic emission monitoring of high temperature regions, *etc.*, are also of interest. Thickness gaging of high temperature tubing is another possibility, if roughness and curvature problems can be overcome.

Dropping down momentarily to room temperature, we have demonstrated that transducer search units (Pana-Probe) employing an obliquely incident SV shear wave are especially suited* for testing materials either very close to their surface (high frequency Rayleigh waves for studying stress-induced corrosion in aluminum alloys) or at interior points such as welds. Most welds, for example, are customarily inspected with an SV wave in the part after a mode conversion from an incident longitudinal wave. The new Pana-Probe method uses incident SV, avoiding angular uncertainties in mode conversion. These probes are

*Because shear waves interact with materials and stress in a manner different from longitudinal waves, shear waves can be used to determine materials properties which are difficult or impossible to obain with longitudinal waves. Testing possibilities are grouped according to whether the incident shear wave enters the specimen normally or obliquely. Applications of shear waves include measurements of temperature, thickness and flaws at elevated temperature, shear wave inspection and characterization of low velocity materials, and determination of stress, strain and material orientations which are sensitive to shear wave polarization. Additional unique advantages of incident shear waves are obtained by mode converting these waves to Rayleigh, Lamb, longitudinal and Love waves. These waves, in turn, may be applied to Rayleigh, Lamb and Love wave inspection at high frequencies, above 10 MHz, or in low velocity solids such as graphites or plastics. Longitudinal wave tests in fluids may be accomplished in extreme environments by using a shear wave buffer rod to isolate the crystal from the exposed portion of the probe. Longitudinal waves can also be refracted more favorably with respect to certain thermometry and flow measurement problems, by using an obliquely incident shear wave.

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extremely durable, usable at all temperatures, more efficient, and when combined with the video probe mounting technique (next paragraph) should give substantial improvement in defining weld quality. Even graphite, plastics, and other low-modulus, low velocity materials have now been tested with waves that previously could not be launched in such materials.

A very recent NDT development, which promises to be rather significant in the seventies, is the successful construction of a video/broad spectrum transducer (Figure 11). This new VIP (Video Inspection Pana-Probe) ultrasonic transducer can

- distinguish interfaces or discontinuities that are as close as one wavelength
- be driven over an entire decade of frequency

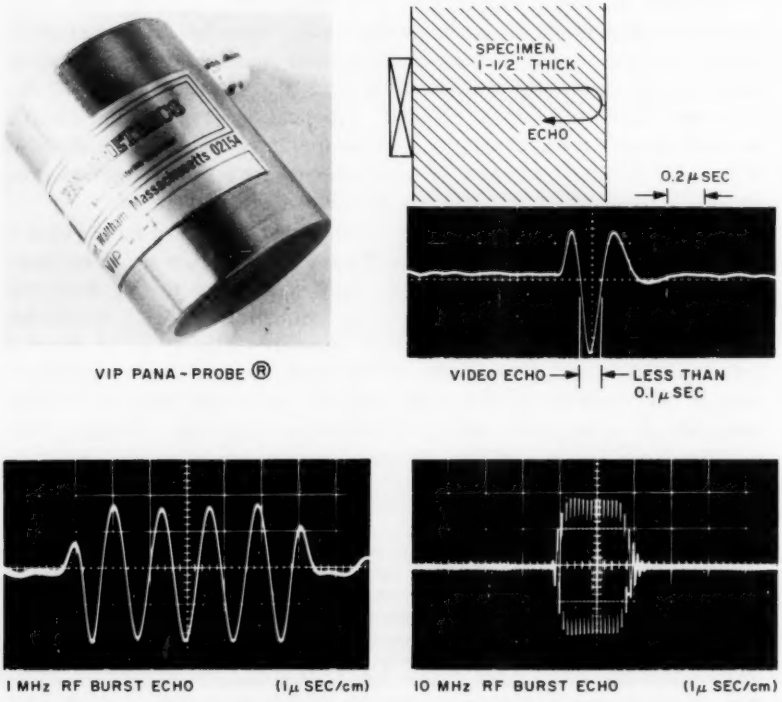

Figure 11 – Ultrasonic echoes using Panametrics' VIP-10-1/2 inch diameter Pana-Probe in pulse echo operation on 1-1/2 inch thick aluminum alloy plate. Oscillograms of the first back echo illustrate the video-pulse performance (for high resolution) as well as the bandwidth of the entire 1 to 10 MHz frequency decade using only one transducer.

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- provide a relatively uniform inspection field (sound pressure amplitude and phase) close to the transducer
- obtain and carry much more flaw information, by virtue of its bandwidth
- be driven by a modulated waveform
- replace 3 to 5 ordinary transducers to cover the spectral band of test frequencies. And its applications are not limited to room temperature.

SUMMARY

Acoustics/ultrasonics research directed toward a long-range goal has led to a better understanding of sound propagation at high temperature—thousands of degrees above ordinary ambient temperatures. Moreover, new data and new questions have been generated. Also, a variety of applications that benefit the Government, particularly the Navy, and basic industries in the U.S. (Table 1) are now possible as spin-off from this research. These spin-off applications, while expecially dramatic at high temperatures, could become significant even at ordinary temperatures.

Potential naval applications to be looked for in the seventies may be easily remembered by associating them with ship construction, from start to finish to operation. As summarized schematically in Figure 12, steel plate may start as a continuous case strand or as an ingot, hot worked into a billet. For the strand, ultrasound will measure skin thickness, temperature, and sump depth. For the billet, ultrasound will make sure the axial "pipe" cavity does not find its way into finished material.

TABLE 1
Ultrasonic Measurement of Process Control Parameters. Sound Propagation Also Depends on Composition, Boundary Layers, Turbulence, Quality, Stress, Anisotropy, *etc.**

Gas Temperature	$T = aV^2$
Liquid Temperature	$T = b - cV$
Fluid Flow Velocity	$U = d(V_2 - V_1)$
Gas Pressure	$P = e\sqrt{V}/\alpha$
Gas Density	$\rho = f/\alpha V^3$
Viscosity	$\eta = gV\alpha$
Liquid Level or Thickness	$\chi = ht$

*Legend: a, b, ..., h are constants. V is velocity, α is absorption coefficient, t is transit time.

During heat treating and forging, ultrasound will measure temperature and grain size. During welding, ultrasound will monitor weld quality. After the ship is launched, one ultrasonic ear may be tuned for corrosion or erosion, and another "acoustic emission" ear tuned for incipient failure of welds or other stressed areas. Power plant temperature,

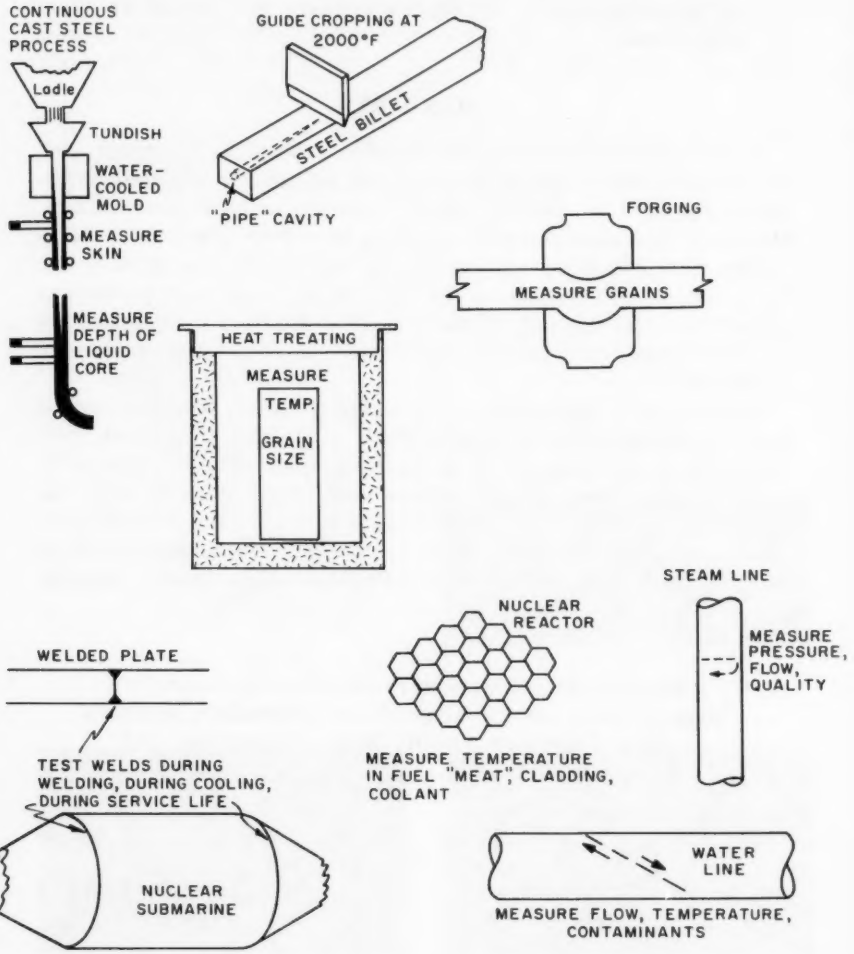

Figure 12 – Typical naval applications of ultrasound anticipated in the seventies, based on research already accomplished in the sixties. Measurement environments include high temperature and high flux. Remote sensing, plus "non-disruptive" measurements that do not perturb the system, are included.

(Continued on Page 32)

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Optical Communication

F. W. Quelle
Office of Naval Research
Boston, Massachusetts

At the time of the development of the laser, one of the characteristics most discussed was their large information bandwidth capacity. In the intervening years, most military activity and commercial interest has been concerned with use of the coherence properties of lasers (the ability to transmit large amounts of energy to distant points) together with some moderate interest in holography. The communication possibilities have been largely neglected. Slowly this situation is beginning to be rectified.

From the point of view of communications, bandwidth requirements have over the years grown at a prodigious rate. The accompanying figure illustrates the rate of opening up of new frequencies as a function of time and shows an increase in spectrum utilization at a rate of about a decade every seven years. Two interesting observations can be made from these curves. First is that significant military and amateur application follows invention by about 15 years, whereas wide-spread commercial application follows invention by about 25 years and furthermore there is no evidence to support the shortening of the time scale between invention and application. The second observation that may be made is that the military can expect to be involved in the use of optical frequencies for communication in the 1980's. Lest we become too carried away with our projections, it is safe to conclude x-ray communication is not likely to be in vogue in the year 2000.

As illustration of todays technology and planning, the Bell Telephone Company is contemplating the orbiting of a 3 GHz bandwidth microwave system using 18-21 GHz up and 21-24 GHz down. The antenna radiation pattern would be about 3000 miles wide at synchronous altitude assuming a small 3 foot dish. By using Saturn booster to place a large precision antenna, the lobe pattern could be reduced to about 100 miles diameter. Couple this one requirement with the many other legitimate interests and requirements and it's not too hard to see how we will run out of parking space for synchronous satellites. It is at this point that optical communication begins to offer real interest. Certainly for wide bandwidth satellite to satellite use and possibly for satellite to ground communication provided the receiving site can be selected, lasers offer attractively interesting possibilities. NASA will orbit an experimental 200 MHz bandwidth CO_2 system in the ATS-F satellite.

Not all interest in optical communication is in connection with satellites. The Bell Telephone Company feels that cloud cover will preclude satellite to ground optical communication in the vicinity of most major cities but is exploring the possibility of using light pipes and optical fibers. They have successfully operated a triangular buried pipe range, but find that without recollimation, straightness requirements will be impossible to meet under field conditions and with recollimation along the pipe losses are currently intolerable. Glass fibers on the other hand have had too high an attenuation to be considered; however, recent developments in ultrapure glasses are allowing attenuations of as little as 50

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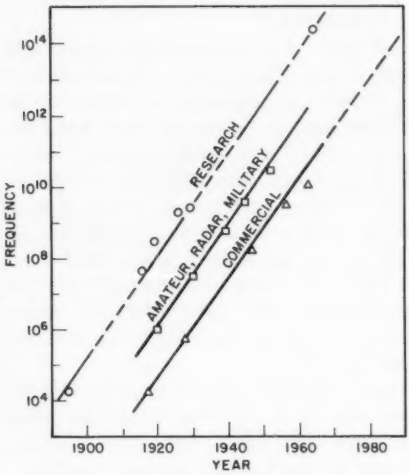
db/Km. Work is also being pursued on micro-optical circuit techniques which will permit fabrication of micro-optical repeaters consisting of an integrated circuit detector-amplifier-semiconductor light source which could be economically placed at several to the mile intervals along an optical fiber transmission line. Bell Telephone Labs was unaware of our development of a 1.06 μ semiconductor laser source at Bell and Howell under the ONR-ARPA (Advanced Research Projects Agency) contract at which frequency optical amplification of the readily modulatable signal is possible. For this communication application, the development of an optically pumped ND-YAG fiber laser would be of interest. Such a device could be profitably used either as a high level repeater or in conjunction with a miniature 1.06 micron semiconductor repeater.



Utilization of the communication spectrum

Modulation and demodulation of the extremely wide bandwidths possible with optical communication present some rather formidable problems. Lockheed has designed and constructed and electro-optical polarization modulator which produces about a 50 percent amplitude modulation at 1.5 GHz on an argon ion laser beam. This carried is FM modulated with a bandwidth of 500 Mhz using the entire RF spectrum from about 10 Mhz to 500 Mhz as the signal source. The modulated beam is detected across the room with a broad bandwidth solid state detector. Although at this wavelength photoemissive detector would appear to offer sensitivity advantages, none of the currently available wide band photoemissive detectors will function in this application because their current multiplication is much too high for the intensity of the signal that is required to carry this information bandwidth. All wide band detectors currently in use have actually been designed to receive relatively narrow band signals over a wide band of frequencies rather than signals covering their entire bandwidth capability. In demonstration of this equipment, several TV sets tuned to various channels,

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a computer and several other electronic apparatus were operated through the link. All showed no observable degradation in quality when connected through the laser link. Further work will be required to increase the modulation bandwidth and develop multiplexing modulation techniques. As mentioned above, development of appropriate wide band detectors will also have to take place. As bandwidth capabilities increase, detector multiplexing by scanning the photocurrent may also be required.

The ONR/ARPA laser program currently is initiating an effort to advance the state of the art in wide bandwidth optical satellite communication. Originally, it was felt that a frequency doubled YAG system taking advantage of the better sensitivity of detectors available in the green region of the spectrum would prove to be superior; however, recent developments in 1.06 micron photoemissive detectors and an increased appreciation of the reliability problem makes the use of frequency doubling with its temperature sensitive phase matching conditions appear somewhat less attractive. Current thinking is centered on a simple Nd-YAG source, possibly sun pumped to further reduce dependency on electronic devices of which the flash lamp is probably the weakest element, and a high sensitivity 1.06 micron photoemissive detector. In a contract being initiated at Lockheed, an ultrastable Nd-YAG source will be developed and modulation of this beam with a wide band (500 Mhz) modulator will be explored. (Modulation at 1.06 microns will prove to be somewhat more difficult than in the green). The spatial modulation characteristics of the output beam will also be investigated. It is anticipated that this will be the first in a series of contracts designed to advance the state of the art in wide band optical satellite communication.

New Development to Improve Naval Research Radar at Chesapeake Beach, Md.

A new diamond-shaped radar feed system designed for efficiency and simplicity has been developed for Naval Research Laboratory's Tracking Radar at Chesapeake Beach, Md.

The new system reduces the complexity of the microwave processing equipment, retains the efficiency of conventional four and five horn feeds and, at the same time, lends itself to dual polarization. Its highly symmetrical radiation pattern will prevent extensive loss of energy to side lobes and sub-reflector spillover and diffraction losses.

The X-band monopulse feed/comparator system was built by RCA's Missile and Surface Radar Division, under contract to the Naval Research Laboratory. It has already been delivered and is expected to soon be installed on a Cassegrainian-type radar system.

Incorporating a feed design originally developed by RCA for use on the AN/FPS-16 radar, the system will meet wideband frequency requirements for the radar's seven-foot diameter dish-type tracking antenna.

The Naval Research Laboratory's Chesapeake Bay Division, located forty-two miles from Washington, D.C., provides unique services and facilities. Its facilities includes wide open overwater areas, equipment for evaluating automatic fire control and tracking radar, and a host of apparatus for conducting special studies in the field of sound, radio, mechanics and optics.

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Rear Admiral Carl O. Holmquist Installed as Chief of Naval Research

RADM Carl O. Holmquist, USN, was installed as Chief of Naval Research, relieving RADM Thomas B. Owen, USN, in a change-of-command ceremony at the Naval Research Laboratory on June 1, 1970, RADM Holmquist has served for eleven months as Deputy and Assistant Chief of Naval Research in the rank of Captain.

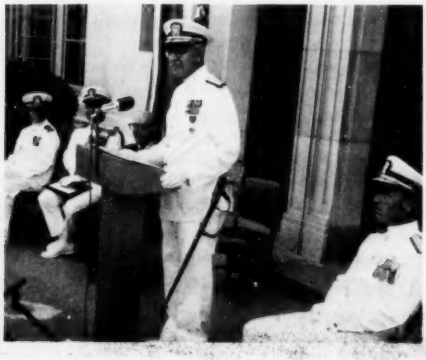
RADM Owen, who retired from the Navy, has been nominated by the President for the post of Assistant Director of the National Science Foundation for National and International Programs. During the change of command ceremony, RADM Owen was presented the Distinguished Service Medal by Dr. Frosch, Assistant Secretary of the Navy.

A native of Salt Lake City, Utah, RADM Holmquist is a member of the Naval Academy accelerated Class of 1943, graduating with honors in June, 1942. After serving aboard a destroyer in World War II during several Pacific campaigns, he became a Naval Aviator in 1945. He later studied at the Naval Postgraduate School and the California Institute of Technology, receiving a Ph.D. degree in Aeronautics from the latter school in 1953.

Among other assignments during his naval career, RADM Holmquist has been Chief Engineer of Flight Test at the Naval Air Test Center and Experimental Officer at the Naval Weapons Center, China Lake, California. RADM Holmquist has also commanded the Naval Training Device Center and the Naval Missile Center, Point Mugu, California.

RADM Holmquist is well known for his numerous contributions to scientific journals and other periodicals, particularly the U.S. Naval Institute *Proceedings* and various editions of the *Naval Review*. Recently he received the annual Award of Merit from the U.S. Naval Institute for his articles.

He is married to the former Lavinia Ervin of Santa Monica, California, and has four children, two of whom are Midshipmen at the Naval Academy.



RADM Owen reads his orders

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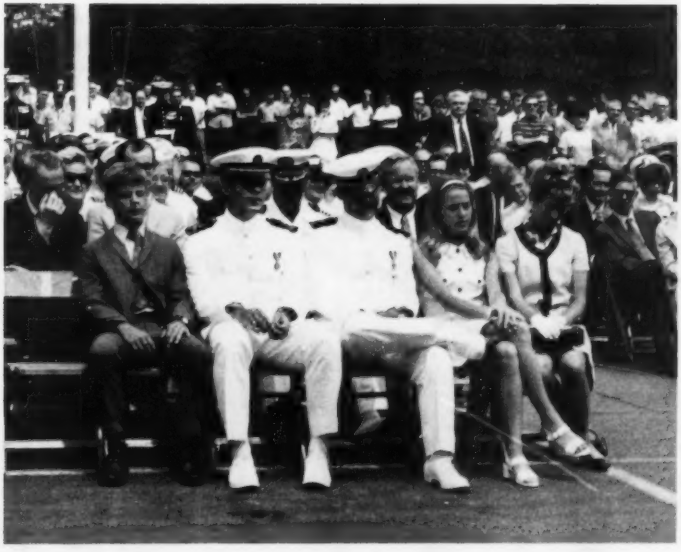
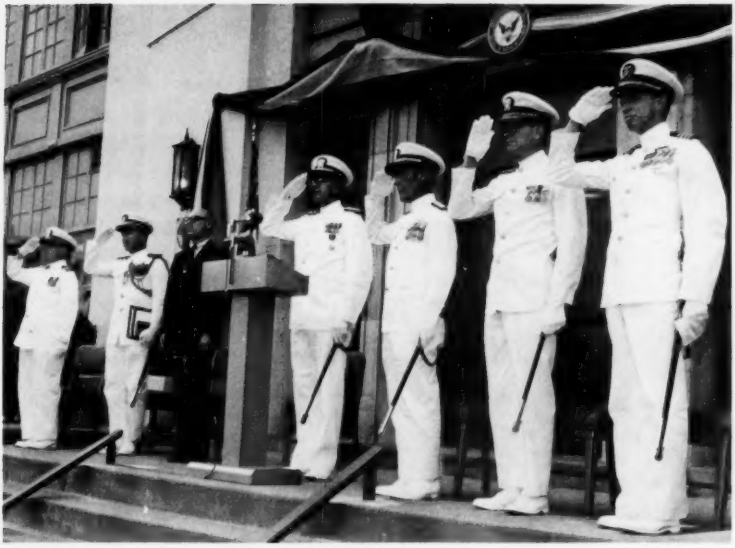
RADM Carl O. Holmquist accepting his new duties as Chief of Naval Research



The Holmquist family during the change of command ceremony. From L to R: Gunnar, Kurt (a Midshipman First Class at Annapolis), Derek (a Midshipman Third Class at Annapolis), Kristen, and Mrs. Holmquist.



Standing at attention when the colors were retired during the change of command ceremony. From L to R: CAPT John T. McLaughlin, Chaplain, USN; CAPT H. Duff Arnold, aide to Dr. Frosch; the Honorable Robert A. Frosch, Assistant Secretary of the Navy for Research and Development; RADM Thomas B. Owen, departing Chief of Naval Research; RADM Carl O. Holmquist, newly installed Chief of Naval Research; RADM Donald D. Chapman, JAG; and CAPT James Matheson, Director of the Naval Research Laboratory.

RADM Owen, RADM Holmquist, and Mrs. Holmquist receiving guests at the reception following the ceremony. Mrs. Owen, who stands to her husband's right, is blocked from view.

On the Naval Research Reserve

NRRC 3-8 News

"Neither rain or snow....." echoed in the ears of LT Frank Berlandi, USNR, of NRRC 3-8, New York City, as he served on active duty for three days during the post office strike. NRRC 3-8 had the unique experience of being the only Research Company in the NYC area whose pay status members were included in the activation of Reserve Components for postal service.

Recently LCDR Harold Brewster, USNR and LCDR Frank Zuccoli, USNR, served as Navy Awards team judges at the New York City High School Science Fair and LCDR Brewster, who is also head of judges for the New York City Borough finals for the Bronx, subsequently assisted in the presentation of the Navy Awards to the winners.

Many of the members participated in ACDUTRA over the past year both at sea and on the job training. Contributions were made to the Navy during these tours of duty ranging from shipboard powerplant controls and nucleonics to jet engine exhaust smoke studies.

NRRC 5-10 Marks 20th Anniversary

The Officers Club at the National Naval Medical Center Bethesda, Md. was the scene of a dinner party celebrating the twentieth anniversary of Naval Reserve Research Company 5-10. Approximately forty past and present members, accompanied by their ladies, joined in the festivities. The highlight of the program was an after dinner address by Senator Charles McC. Mathias, Jr. (R-Md.). The meeting ended following a question and answer session.

NRRC 9-14 Report

The members of NRRC 9-14, Madison, Wisconsin, participated in a Seminar on Human Physiological Performance, conducted at the Biodynamics Laboratory of the University of Wisconsin this fall. The seminar was conducted by Dr. Bruno Balke, internationally recognized authority on cardiorespiratory fitness and sports medicine. Seminar participants experimented with various types of laboratory equipment and discussed various techniques used in biodynamics research.

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News of Naval Reserve Research Company 8-3

Four retired Naval Reservists were honored by Naval Reserve Research Company 8-3, College Station, Texas for their contributions to their nation and community. CAPT Richard H. Ballinger, CDR Bill C. Moore, CDR Robert E. Schiller, Jr., and CDR C. Kinney Hancock were presented "planks" by the members of the Company. The presentation was made by the Company Commanding Officer, CDR Ronald Darby.

Each of the four officers served on active duty in World War II, for four or more years, and continued in the active reserve for twenty-five or more years. The "planks" were fashioned from hardwood decks, removed from Nagle Hall on the campus of Texas A&M University. Nagle Hall was the first meeting place of Research Company 8-3. The Company was activated in 1949 and CDR Schiller was a member of the original "crew."

NRL's New Director

CAPT Earle W. Sapp, USN, became the Director of NRL on June 30, relieving CAPT James C. Matheson. CAPT Sapp, comes to the Laboratory from the Office of the Director of Defense Research and Engineering where he was Deputy to the Assistant Director (Ocean Control).

CAPT Sapp attended Duke University, where he was enrolled in the NROTC program. In March 1947, he received his degree in Physics and his commission as Ensign, USN. During his subsequent naval career, CAPT Sapp acquired extensive experience in research and development, as well as broad operational and command experience in the fleet. His R&D experience includes project assignments in fleet evaluation activities, in the Office of Naval Research, and in experimental ships assigned to Navy laboratories and the Operational Test and Evaluation Force.

Research Notes

ONR Moves to Virginia

In June the Office of Naval Research moved across the Potomac to North Arlington. The new offices are a short distance from downtown Washington with visitor parking spaces in the building. The address is:

Office of Naval Research
800 N. Quincy Street
Arlington, Virginia, 22217

Howard Wighton, Navy Contract Negotiator Dies

Howard Patrick Wighton, a financial adviser and contract negotiator for the Office of Naval Research, died after a heart attack while on a business trip to Boulder, Colorado 20 May 1970.

Mr. Wighton, a native of Yonkers, N.Y., attended Columbia University and Pratt Institute in New York. He worked as an accountant with A. A. Andersen Co. there and as an employee of the Bank of the United States.

He was a contract negotiator with the Navy's special devices center on Long Island before coming to Washington in 1951 to join the Office of Naval Research. Mr. Wighton's responsibilities as contract negotiator included transactions with many universities and corporations.

Mr. Wighton is survived by his wife, Marguerite of 9614 Dilston Rd., Silver Spring; his father, and four brothers.

Molecular Hydrogen Detected in Interstellar Space

Molecular hydrogen has been detected in interstellar space for the first time, by instrumentation flown on an Aerobee rocket from White Sands Missile Range by the Naval Research Laboratory on March 13, 1970. This is a significant finding in that molecular hydrogen is thought to be a very important constituent of the interstellar gas, but is unobservable with ground-based instrumentation. Although much indirect evidence for the presence of large amounts of molecular hydrogen in space had been accumulated, there had been no direct measurement thereof before this rocket flight. Dr. George R. Carruthers, a research physicist at the Naval Research Laboratory became the first to detect the molecules' long suspected presence by developing an electronic image-intensifier.

Hydrogen is the most abundant element in the universe. Astronomical studies have revealed that hydrogen (in the atomic form) constitutes 85 percent of the total mass of the sun, stars, and emission nebulosities. Hydrogen is also believed to be the major component of the interstellar gas but, here, it is much more difficult to determine the composition since the interstellar gas is generally cold and in an unexcited state.

Atomic hydrogen in the interstellar gas can be detected by its radio-wave emission at 21 centimeters wavelength. Molecular hydrogen, however, can be detected only by its absorption of ultraviolet radiation emitted by very hot stars. This radiation, however, is also absorbed by the Earth's atmosphere. Therefore, to observe this radiation, instruments must be carried above the atmosphere by sounding rockets or satellities. Atomic hydrogen, also, can be measured by its absorption of ultraviolet light, at a somewhat different wavelength from the range in which molecular hydrogen absorbs.

The first rocket observation of stars in the wavelength range in which molecular hydrogen could be detected was made by the Naval Research Laboratory in March 1967. The

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result was negative, indicating that there was no appreciable amount of molecular hydrogen in the line of sight to the stars observed. Molecular hydrogen is the stable form of hydrogen at ordinary temperatures and pressures. However, in interstellar space, molecular hydrogen can be broken up into atoms by ultraviolet light (the same as that with which one hopes to observe it). On the other hand, molecular hydrogen can be re-formed from atomic hydrogen only in the presence of dust particles, which act as catalysts for the recombination of two hydrogen atoms to form the hydrogen molecule. Therefore, it was predicted that the best chance for observing molecular hydrogen would be in regions of known dense dust clouds, where the recombination of atoms to form molecules would be fast enough to keep up with the breaking-up of the molecules by ultraviolet starlight. Radio astronomers had accumulated much indirect evidence for the presence of molecular hydrogen in these dense clouds, mainly in the form of an unexpected decrease in the radio emission of atomic hydrogen in these clouds, and the radio detection of more complex molecules such as ammonia, water vapor, and formaldehyde. An infrared observation of the Orion Nebula also indicated the possible presence of molecular hydrogen in a dark cloud which was very close to a group of very hot stars, creating a condition in which the molecular hydrogen could give off infrared radiation which it would not give off in its usual cold, unexcited condition.

The NRL rocket flight of March 13, 1970 observed the star Xi Persei, a hot star whose light in known to be partially obscured by dust between it and Earth. The observations indicated very definitely the characteristic absorption spectrum of molecular hydrogen, the amount of molecular hydrogen was determined to be well in excess of one-tenth of the amount of atomic hydrogen along the same path. Since the density of dust particles in the line of sight to Xi Persei is actually relatively small, this indicates that in the more dense, dark dust clouds, which almost totally absorb the light of stars beyond them, the hydrogen is almost entirely molecular.

Astronomers have known for many years that stars form in dark dust clouds, by a process of condensation (much as raindrops are formed from water clouds). Therefore, since the newly formed stars are observed to consist mostly of hydrogen as do most other stars, and atomic hydrogen is observed to be deficient in these clouds, it was conjectured that molecular hydrogen plays an important role in star formation. A contracting gas cloud which contains molecular hydrogen can give off the heat of compression more readily than one which does not, allowing the contraction to proceed more rapidly than would otherwise be possible. Hence, the discovery of molecular hydrogen provides confirmation of theories of star formation from the interstellar gas.

(Continued from Page 22)

pressure, flow and steam quality will be measured ultrasonically. Such applications of ultrasound, complementing other independent measurements already on board, should provide the man in charge of an operation with accurate information on the materials, power, processes, and quality on which his mission depends.

The above applications are not restricted to naval situations. Most readers will recognize similar situations in their own fields—nuclear systems, aircraft engines and components, structures, chemical process plants, materials processing, *etc.*

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U.S. Naval Research Laboratory Presents Pioneer Radar Receiver to Smithsonian Institution

The Smithsonian Institution has received another wonder of the mid-twentieth century destined to become a museum piece in its Hall of Electricity.

The Director of the Naval Research Laboratory Captain James C. Matheson, presented the first radar receiver developed by scientists at NRL to Dr. Bernard S. Flinn, Chairman of the Smithsonian Institution's Department of Science and Technology and Curator of Electricity. This device was first successfully tested on April 28, 1936, when it detected and ranged an aircraft in flight 25 miles away.

Radar, the Navy's acronym for radio detection and ranging, is considered to be the most revolutionary new weapon of World War II and the instrument which shaped the course of victory in many historic battles of that and later wars. This pioneer development by the Navy has now become a multi-billion dollar business involving uses on aircraft, ships, boats, police cars, and other surveillance systems throughout the world.

American radar came as a by-product of radio research by a small group of Naval Research Laboratory scientists. Subsequent developments from the original system have lead to improved and expanded uses of radar far beyond anything envisioned in the original concepts.

NRL developed the first shipboard radar unit and installed on the battleship USS NEW YORK in 1938 for sea trials. Fleet exercises in March 1939 proved radar's capability and importance in the detection of aircraft and projectiles in flight as well as ships at sea. It also proved valuable as an aid in navigation during darkness and poor visibility. More sophisticated systems were added to the greater percentage of ships involved in World War II, thus enhancing the chances for a final Allied victory.

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